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USING ARC/INFO TO MONITOR SPACE SHUTTLE LAUNCH EFFECTS AND VALIDATE A SPATIAL PREDICTIVE MODEL

Space Shuttle launches produce localized acidic deposition. The Rocket Exhaust Effluent Diffusion (REED) model predicts the spatial pattern of deposition pre-launch. Actual ground patterns are mapped in the field post-launch. An ARC/INFO database was constructed by digitizing the REED model output and ground field maps. Statistical analysis of data derived from ARC/INFO showed that the direction of launch cloud movement did not significantly differ from that predicted, but the REED model overpredicted both area that received deposition and the maximum distance deposition occurred from the pad. Cumulative ground deposition maps showed that near-field deposition occurred within 1600 meters of each launch pad. Total area impacted has been 66.5 ha from Pad 39A launches and 52.7 ha from Pad 39B. Far-field deposition has occurred over a total of 18148 ha. In this paper we demonstrate the utility of storing, analyzing and querying spatial cumulative impact data as well as provide a means for validating a spatial model in a GIS context.

INTRODUCTION

Space Shuttle launches produce direct localized impacts on the surrounding environment through the formation and dispersion of an exhaust cloud primarily consisting of carbon dioxide (CO_2), water (H_2O), aluminum oxide (Al_2O_3), and hydrogen chloride (HCl) (NASA 1979). Exhaust cloud formation results from combined effects of igniting the Solid Rocket Motors (SRM), the Space Shuttle Main Engines, and the simultaneous release of approximately 1.14×10^6 L of sound suppression and cooling water on the pad. Atomization of the deluge water occurs; water droplets coagulate with Al_2O_3 particulates and rapidly scavenge HCl gas producing acidic deposition (Anderson and Keller 1983, 1990). Typically this ground cloud is directed horizontally northward by the structure of the flame trench, then rises (Knott et al. 1983) to a stabilization height (Bjorklund et al. 1982), and is then carried and dispersed by prevailing winds.

Rocket Exhaust Effluent Diffusion Model

The Rocket Exhaust Effluent Diffusion (REED) model was developed to predict launch cloud deposition on a near real-time basis (Stephens and Stewart 1977, Bowman et al. 1984). The predictions are used to assess the extent of launch deposition and for pre-launch preparation. Predictions are made based on inputs of meteorological data from rawinsonde readings that include vertical profiles of wind direction, wind speed, air temperature, atmospheric pressure, and relative humidity from the surface to 3048 m (10000 ft).

Observations from early Space Shuttle launches (Bowie 1981, Knott 1982) showed that the model correctly predicted direction of launch deposition but placed the deposition much farther from the launch site than actually occurred. In 1984, the model was modified to predict gravitational HCl (hydrochloric acid) deposition (Bowman et al. 1986). The revised model predicted higher deposition near the launch pad declining with distance in qualitative agreement with observations (Schmalzer et al. 1986).

Near and Far-field Deposition

Based on observed impacts and deposition mechanics, the exhaust cloud deposition has been divided into two categories, near-field and far-field. Near-field deposition is that occurring from the ground cloud sweeping turbulently across the ground. The SRM's exhaust is initially directed northward by the pad structure causing near-field deposition to be concentrated on the north side of each launch facility. Near-field deposition has occurred within 0.5-1.5 km of the launch pads (Dreschel and Hall 1985, 1990; Schmalzer et al. 1985). For each launch, the area impacted by near-field deposition has been mapped based on visible effects on vegetation and structures.

Far-field deposition occurs after the ground cloud rises and moves with prevailing winds. Areas receiving far-field deposition vary with meteorological conditions more than the near-field component. The ground track of deposition from every launch has been mapped by field surveys.

METHODS

The REED Model

The REED model is run prior to each Space Shuttle launch. Rawindsonde data are down-loaded to the mainframe computer where the REED model is supported. The map produced shows the geographic region of potential deposition by the launch exhaust cloud, and isopleths of predicted HCl deposition ranging to 25 mg/m^2. The map from the last model run for each launch has been digitized for GIS analysis; the 25 mg/m^2 isopleth was used. For the earlier launches, the archived rawinsonde files were retrieved and run in the revised REED model for consistency.

Mapping Ground Cloud Deposition

The footprint of the exhaust cloud is mapped several hours after each Space Shuttle launch by field observation of launch deposition on vegetation and structures. Near-field effects are readily mapped based on the predictable direction of the cloud, the relatively small area affected, and the obvious vegetation damage from HCl deposition.

Far-field deposition occurs as spots on vegetation and structures such as pipelines, railroad tracks, etc.; spotting may include small acidic burns from "wet" deposition or may be dry residue, primarily Al_2O_3 (Knott et al. 1983). The REED model output produced at the time of launch is used to help map the far-field deposition pattern. Structures and vegetation are examined for visible deposition in these areas. Locations of deposition are recorded on topographic quadrangle maps. Boundaries of deposition are determined by searching in a given direction until deposition can no longer be detected, or the cloud track moved out to sea, or otherwise can not be followed. After each field survey is complete, the maps of actual deposition are digitized into ARC/INFO.

Cumulative Deposition Maps

Individual maps of the actual deposition were unioned together to produce cumulative deposition patterns for both Shuttle launch facilities. Five different cumulative maps were created: two of these maps showing near-field deposition patterns for Pads 39A and 39B, two maps showing far-field deposition patterns for Pads 39A and 39B, and one map showing combined far-field deposition patterns for both Pads 39A and 39B.

Before the unions were performed, additional items were added to the polygon attribute tables (PAT) for each of the actual maps. The first item performs as a counter when these individual files are unioned together. This item gets a value of one per individual actual map. The second item is used to hold the name of that launch. This second item, when combined with the first, allows ARC/INFO not only to know how many times a particular polygon has been impacted by deposition but which launches have deposited in each polygon of the unioned files.

Predicted vs. Field Observations

ARC/INFO (ESRI 1989) was used to measure four spatial variables for both the modeled and ground-truthed launch cloud maps. These variables consist of the direction the cloud traveled, the distance traveled from the pad, the area of deposition, and the amount of overlap between actual and predicted areas. The modeled and actual launch files were unioned to yield the amount of overlap between the two maps. Areas were taken directly from the PATs and directional measurements were made by overlaying a template marked in degrees. Distances were obtained by interactively measuring each cloud from the center of the launch pad to the cloud's farthest extent. Area, distance, and direction were compared by considering the predicted and ground measures for each launch to be paired samples and testing whether the difference scores differed from zero using paired sample t-tests (SPSS Inc. 1988). Difference scores were normally distributed (Kolmogrov-Smirnov test, SPSS Inc. 1988). Predicted and actual distances and areas were also compared by taking the differences between the model and actual ground distances and areas, then dividing by the area or distance predicted to be impacted for each launch. For launches where the cloud went out to sea, data on distance and area of actual deposition were not available and direction data were not comparable to those where the deposition pattern was over land. Therefore, statistical comparisons were only made for cloud pathways over land.

RESULTS

Predicted vs. Field Observations

The REED models predictions ranged from being very similar to actual patterns observed in the field (Figure 1) to being dissimilar (Figure 2). These figures represent the extremes where the model performs well and where the model performs poorly. In both cases, the REED model overpredicted the area and distance from the pad that were actually impacted. Twenty-four of the forty-three launches produced deposition patterns over land, while those of the other nineteen launches traveled offshore, preventing detailed mapping and tracking of these events. Predicted areas and those measured from field maps differed significantly (paired sample t-test, $t=14.46$, $p<0.001$). The model and ground distances also differed ($t=8.66$, $p<0.001$). Direction predicted by the model and that observed were not significantly different ($t=0.27$, $p=0.787$). Thus, the REED model correctly predicted the direction of the launch cloud, but overpredicted both the distance that the deposition extends from the pad and the area that receives deposition.

The mean percent area overprediction by the model was 77% and the range was 42% to 99.8%. The mean percent distance overprediction was 51%; the range was from -1.9% (one case where the ground cloud exceeded the predicted distance from the pad) to 97%. The proportion of area that received ground deposition and was predicted to receive deposition was determined by dividing the area of overlap by the actual area for each launch. The REED model predicted a mean of 79% of the actual area impacted with a minimum of 15% and a maximum of 100%.

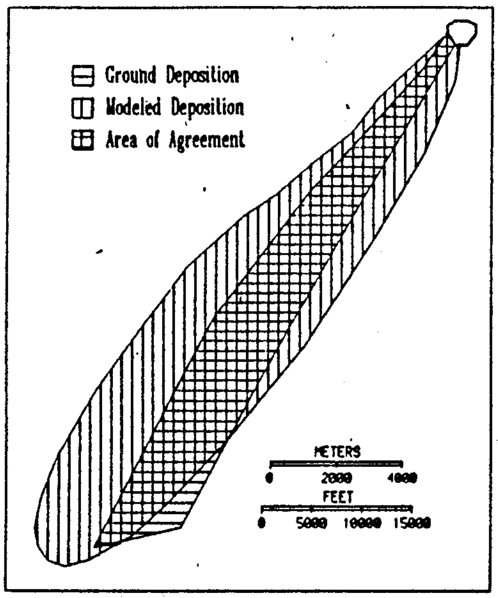

Figure 1. Comparison of modeled and observed deposition paterns from the launch of STS-19. Predicted deposition pattern is from the REED model output; observed is from field survey maps.

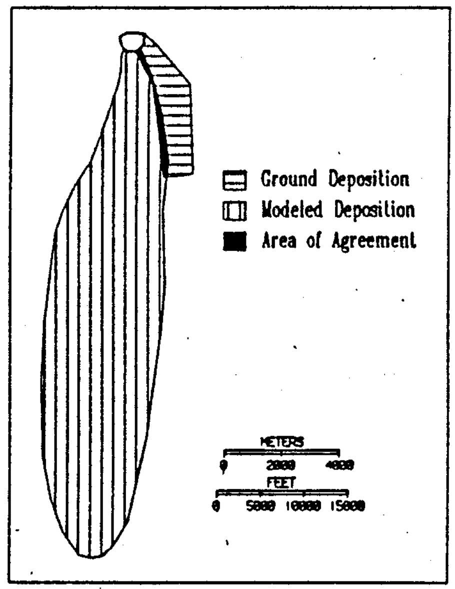

Figure 2. Comparison of the modeled and actual deposition from the launch of STS-27. Predicted deposition pattern is from the REED model output; observed is from field survey maps.

Cumulative Effects

GIS analysis shows near-field deposition to affect areas concentrated north of both pads (e.g., Figure 3) decreasing with distance. The maximum distance that near-field deposition has occurred from 39A is 1547 m and from Pad 39B, 1413 m. The majority of launches (30 of 43) have been from pad 39A. The same distribution (pattern of deposition) occurred at Pad 39B as at Pad 39A, although with smaller total numbers. More total area has been impacted around Pad 39A (66.5 ha) than Pad 39B (52.7 ha), and some areas have received more frequent deposition (Table 1). At Pad 39A, 45% of the total area impacted has received near-field deposition not more than three times, and at Pad 39B, 66% of the area impacted is in this category.

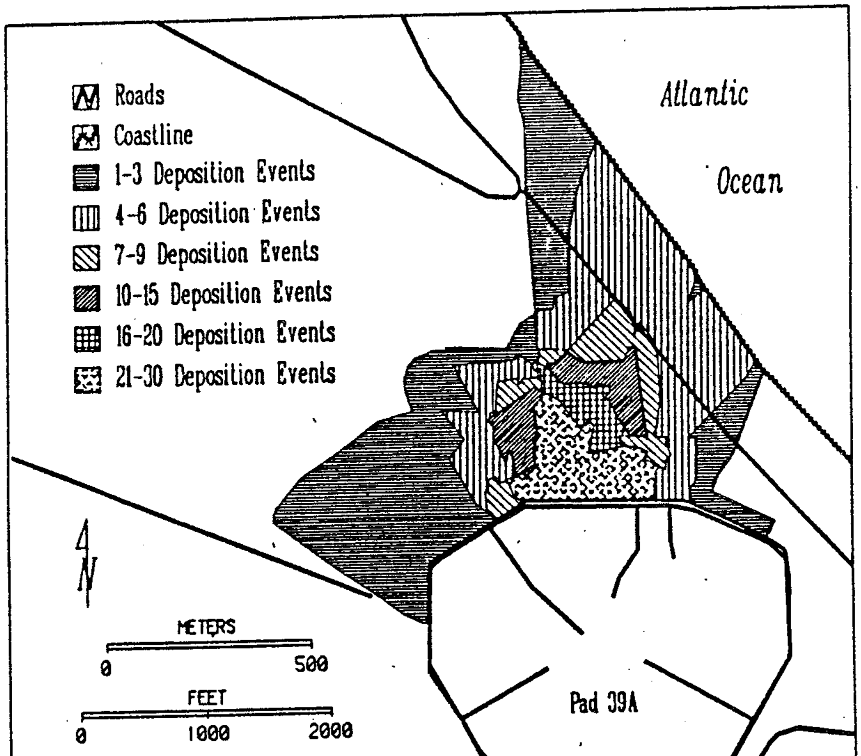

Figure 3. Cumulative pattern of near-field deposition from 43 Space Shuttle launches at Pad 39A. Pattern determined by overlaying observed field maps of near-field deposition.

Table 1. Cumulative areas of near-field deposition from 43 Space Shuttle launches. Areas determined by GIS analysis of cumulative maps created by overlaying field maps of deposition from individual launches.

Number of Deposition Events	Area Impacted (ha) 39A	39B
1-3	29.7	34.8
4-6	20.7	12.3
7-9	4.6	2.8
10-13	-	2.9
10-15	4.1	-
16-20	2.0	-
21-30	5.5	-
Total	66.5	52.7

Far-field deposition has had a more variable pattern (Figure 4) than near-field, and has covered a much larger area (Table 2). A total of 18148 ha has received deposition at least once, but 69% of this area has been impacted only one time and 92% has been impacted not more than three times in 43 launches.

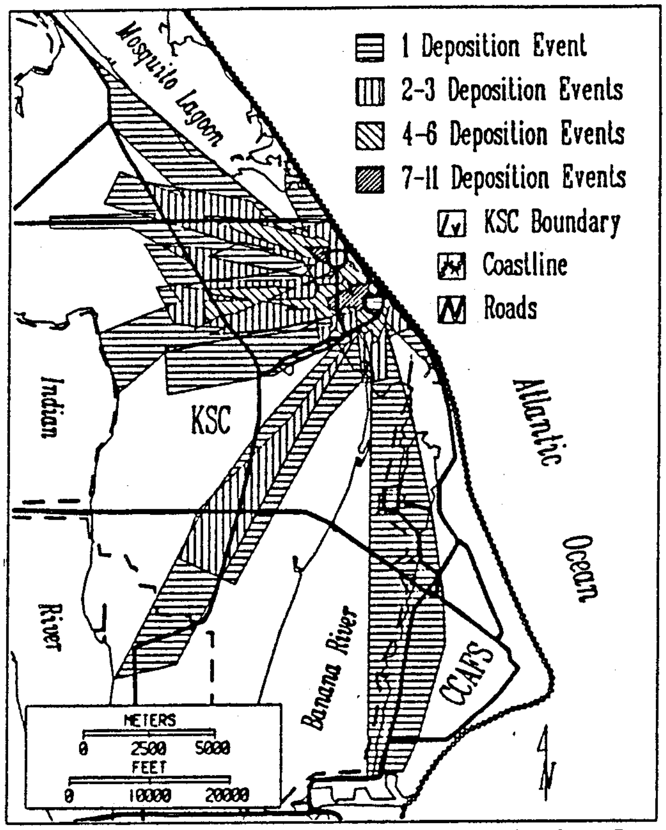

Figure 4. Cumulative pattern of far-field deposition from Space Shuttle launches. Pattern determined by overlaying observed field maps of both pad 39A and 39B far-field deposition.

Table 2. Cumulative areas of far-field deposition from 43 Space Shuttle launches. Areas determined by GIS analysis of cumulative maps created by overlaying field maps of deposition from individual launches.

Number of Deposition Events	Area Impacted (ha)
1	12447
2-3	4337
4-6	1156
7-11	208
Total	18148

DISCUSSION

The data show that the REED model typically overpredicts the area and distance impacted by Shuttle launches while correctly predicting direction. In the majority of cases, the model predicted most of the ground area actually impacted. By using GIS techniques and maps of predicted and actual deposition patterns, we were able to determine quantitatively spatial aspects of the REED model's performance not previously possible. GIS technology allows for both graphical and numerical assessment of spatial data; Zannetti (1990) noted "the powerful use of graphical methods for performance evaluation" in referring to validating models.

The cumulative maps show that a total of 119.2 ha after 43 launches have been impacted by near-field deposition. Near-field deposition remains localized, concentrated north of each launch pad, and has affected a relatively small area. The area that has received far-field deposition is large (18148 ha) after 43 launches and is widely distributed but deposition does not occur frequently at any given location. Maintaining spatial launch cloud deposition data in a GIS data base offers operational as well as scientific advantages. The data are readily accessible for both numeric and spatial analysis as well as spatial queries. The data base can be queried for information on the extent, frequency and origin of deposition as well as the time between deposition events for a particular area of interest.

This paper has demonstrated the utility of using ARC/INFO for monitoring cumulative launch patterns and validating a spatial predictive model. The main elements of individual launch clouds can be isolated and measured within a GIS framework. These measurements can then be used for validating a predictive model. We have also demonstrated that cumulative maps showing number of impacts and origin of impacts can be stored and produced from individual map layers.

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